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Lava production at Soufrière Hills Volcano, Montserrat: 1995–2009

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[1] We estimate that about 1 km³ of andesitic lava has been produced at Soufrière Hills Volcano, Montserrat from 1995 to 2009. There were three major episodes of extrusion, each lasting about 2 to 3.5 years and producing about 280 to 340 M m³ of lava, and one minor episode. Our estimates account for the dense rock equivalent volumetric contributions from the core and talus components of the lava dome, pyroclastic flow deposits and air-fall deposits. By 2005 at least two thirds of the erupted mass has already entered the sea. The average lava flux across the major extrusion episodes has been 3–5 m³s^{−1}, with short-period (10–15 days) pulses up to 10–20 m³s^{−1}. The first and third episodes of extrusion show similar flux histories suggesting similar behaviour of the system ten years apart. Waning flux towards the end of each episode may be caused by declining overpressure in the magma reservoir. **Citation:** Wadge, G., R. Herd, G. Ryan, E. S. Calder, and J.-C. Komorowski (2010), Lava production at Soufrière Hills Volcano, Montserrat: 1995–2009, *Geophys. Res. Lett.*, 37, L00E03, doi:10.1029/2009GL041466.

1. Introduction

[2] Soufrière Hills Volcano (SHV) on Montserrat has erupted about 1 km³ of andesite magma in the fourteen years between 1995 and 2009. It has done so predominantly in episodes of lava dome growth and destruction: 15 November 1995 – 10 March 1998, 27 November 1999 – 28 July 2003, 1 August 2005 – 20 April 2007, 28 July 2008 – 3 January 2009. Between these episodes no new lava was extruded but seismic, geodetic and gas flux evidence indicated ongoing unrest, probably due to basaltic and andesitic magmas continued to interact in the magma reservoir throughout the whole interval.

[3] Most of the andesite magma has been erupted as lava. The lava created a dome with a variety of forms [Watts *et al.*, 2002], and a rockfall-generated apron of talus that surrounds the steep-sided lava core of the dome out to a maximum distance of about 500 m [Wadge *et al.*, 2009]. Larger collapses of the core produced more widely dispersed pyroclastic flows, some of which reached the sea, mainly between 3 and 4 km away. Pyroclastic flows were

also produced, much less commonly, by column collapse [Druitt *et al.*, 2002a], lateral blast [Sparks *et al.*, 2002], hydrovolcanic surge [Edmonds *et al.*, 2006] and as surge-derived flows [Druitt *et al.*, 2002b]. The lava dome has had six collapses that have each involved surveyed volumes of core and talus greater than 20 M m³, on 26 Dec. 1997, 3 July 1998, 20 March 2000, 29 July 2001, 12–13 July 2003 and 20 May 2006. In the latter two cases almost the whole of the dome and talus was transported to the sea in a few hours.

[4] The solid output of the volcano has formed several types of deposit: the dome's lava core, talus apron, pyroclastic flow deposits (including fan-deltas at the coast) and air-fall tephra. The volumes of these deposits have been estimated by different observers in the following ways. When growing, the shape of the dome has been surveyed (on average about every 20–30 days) by photogrammetry or theodolite techniques [Sparks *et al.*, 1998; Herd *et al.*, 2005; G. Ryan *et al.*, Growth of the lava dome and magma extrusion at Soufrière Hills Volcano, Montserrat, West Indies: 2005–2008, submitted to *Geophysical Research Letters*, 2009], supplemented occasionally by ground-based lidar [Jones, 2006] and radar [Wadge *et al.*, 2008]. Pyroclastic flow deposit volumes have been estimated by photogrammetry, GPS-survey and field, helicopter and satellite observations, and air-fall deposit volumes from tephra thickness measurements and mapping. A discussion of these methods and their uncertainties associated with these estimates is given in the auxiliary material.⁷ Independently, the volumes of the marine deposits have been measured in a series of research cruises.

2. Volumetric Budget

[5] The volumetric budget for most of the first episode of extrusion (November 1995 – December 1997) was presented by Sparks *et al.* [1998] and we use many of the accounting assumptions of that study. Scientists at the Montserrat Volcano Observatory have subsequently surveyed the lava dome and estimated its products and this current compilation is largely based on those data. The mass of andesite magma erupting through SHV attains different bulk depositional densities depending on the dynamics of emplacement on the surface. We account for this by normalising the deposit volumes to a dense rock equivalent (DRE) volume (Figure 1).

[6] Surveys of the lava dome capture the combined shape of the lava core and the enveloping talus, though they must have quite different bulk densities. To account for the separate contributions of core lava and talus to the budget requires assumptions to be made about the boundary

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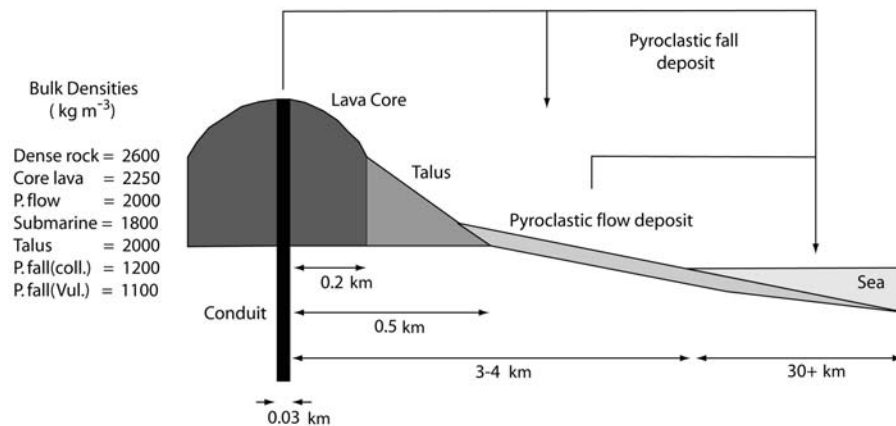


Figure 1. Schematic cross section through the volcano showing the main components of the volumetric budget and their assumed bulk densities. Typical horizontal scales are shown by the arrowed lines.

between them and their densities. A geometrical model with such assumptions is described in the auxiliary material, and this differs from that of *Sparks et al.* [1998], who assumed a single bulk density for the dome.

[7] The volumes of some individual pyroclastic flow deposits can be estimated from their areal extent and field thickness measurements. However, most of the thousands of flow deposits were not mapped individually, particularly the smallest and most readily buried and those emplaced partly offshore. For these cases, the following empirical runout distance (in km up to 4 km) versus volume (M m³) relationship, calibrated using well-observed examples, was used [Calder et al., 1999, 2002]: pyroclastic flow deposit volume = $0.0374 e^{0.7418(\text{runout distance})}$.

[8] Often the exact number of flows of a given runout distance over a one-day accounting period was not known. Such flows were assigned to two classes, “several” and “persistent”, with respective multiplicative factors of 4.5 and 9 used to calculate their combined volumes. Generally, the volume of each pyroclastic flow deposit has been added to the modelled dome volume interpolated linearly to the time of the flow event.

[9] During pyroclastic flow emplacement, surges and buoyant ash clouds advected by winds deposited their load more widely. *Bonadonna et al.* [2002] showed that this typically amounts to about 4–16% of the volume of the pyroclastic flow deposit and we add a value of 15% DRE, as used by *Sparks et al.* [1998], to account for this.

[10] Vulcanian explosions can evacuate magma from considerable depths within the conduit (down to ~5 km [Robertson et al., 1998]) to produce high eruption columns (up to 17 km) and airfall ash deposits usually containing pumice. Following such explosions there is often a hiatus in surface extrusion as the conduit refills. However, not all explosions involve evacuation of conduit magma and it can be difficult to discriminate the two sources. The main contributors to this type of deposit occurred as a series of 88 explosions between 4 August and 21 October 1997 [Druitt et al., 2002a] and a summary list of all such events considered is presented in the auxiliary material. The overall volumetric contribution of about 38 M m³ is modest, though it may underestimate the contribution from fine, distal ash.

[11] Much of the output from the volcano entered the sea, transported by pyroclastic flows and surges, mainly to the

east. An exception to this was the collapse and lateral blast of 26 December 1997 to the south. There have been fewer and smaller pyroclastic flows entering the sea to the west. Bathymetric and coring surveys around parts of southern and eastern Montserrat were undertaken in July 1998, January 1999, March 2002 and May 2005 [Deplus et al., 2001; Hart et al., 2004; Trofimovs et al., 2006, 2008; Le Friant et al., 2009]. By 2005 the eastern submarine deposits showed five turbidite units each of which were correlated with separate periods of the eruption: May 1996 – January 1997, and four collapse events: 3 July 1998, 20 March 2000, 29 July 2001 and 12–13 July 2003 [Trofimovs et al., 2006]. These submarine surveys and the derived deposit volumes (auxiliary material) do not extend into the shallow water around the fan-deltas and we have estimated separately the volume of submarine near-shore/subaerial fan-delta sediment deposited from 1995 to 2009 as about 113 M m³ DRE (auxiliary material). Between November 1995 and May 2005 we can account for a volume of about 443 M m³ of marine sediment, including 100 M m³ assumed for the near-shore component. This is about 66% of the output of the volcano over this period.

3. Episodic Nature of Lava Extrusion

[12] From 1995 to 2008 there were three episodes (1–3) of lava extrusion each lasting about 2–3.5 years and extruding volumes of about 280–340 M m³ DRE with intervening pauses of about 1.5–2 years (Figure 2 and Table 1). Since July 2008 there have been two, month-long, periods of extrusion separated by three months, which we term extrusive episode 4 (Table 1). After a further pause of 10 months, extrusion resumed in October 2009 (not discussed any further). It may be that the change in eruptive behaviour since July 2008 is of major significance for the volcanic system that requires a change in terminology, but this is not yet clear.

[13] The eruption-averaged DRE flux of magma through the volcano from 15 November 1995 to 1 August 2009 was 2.3 m³/s. The average flux for episode 2 was lower than for episodes 1 and 3. Not only is the average value of flux for episodes 1 and 3 similar, but so are the shapes of the cumulative volume curves (Figure 2). Both episodes began with low fluxes that accelerated after 200–300 days,

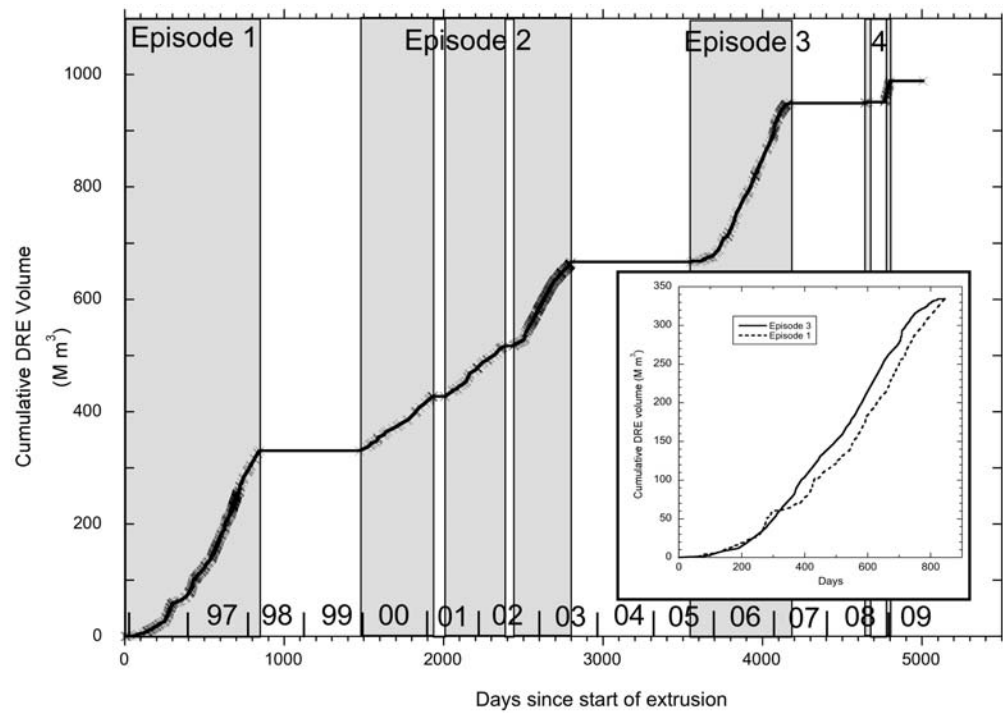


Figure 2. Cumulative DRE volume of lava erupted from SHV from 15 November 1995 to 1 August 2009. Episodes of lava extrusion are shown shaded (note the two short periods of no extrusion in the second episode). The years are shown by the larger figures along the abscissa. The inset plot shows the normalised cumulative curves of episodes 1 and 3.

followed by a dominant linear efflux and a deceleration in the last 100–200 days (Figures 2 and 3). In contrast, episode 2 begins with a more constant, lower flux, though this is broken by two short periods of no extrusion in March–May 2001 and June–July 2002. It is only in the last 300 days of this episode that the flux rises to higher values and decelerates to the end (Figures 2 and 3).

[14] There have been several periods in all episodes when the lava flux has risen to levels greater than $5 \text{ m}^3/\text{s}$, and occasionally as high as $15\text{--}20 \text{ m}^3/\text{s}^{-1}$ [Sparks *et al.*, 1998;

Ryan *et al.*, submitted manuscript, 2009; J.-C. Komorowski *et al.*, Pumiceous deposits from the July 2008 and January 2009 contrasted Vulcanian explosions at Soufrière Hills Volcano (Montserrat, West Indies): Implications for hazards, manuscript in preparation, 2009], though the frequency of quantitative measurement, represented by the 10-day sampling interval in Figure 3, does not always capture this. During 1997 some of these high-flux periods coincided with the first stage of a deformation cycle lasting 35–50 days [Voight *et al.*, 1999; Sparks and Young, 2002] that has been

Table 1. Characteristics of the Episodes of Extrusion and Pauses

Episode	Dates	Duration (days)	DRE Volume (M m^3)	Extrusion Rate (m^3/s)	Character
1	15 Nov 95–10 Mar 98	846	331	4.5	Initial phreatomagmatic explosions and large to moderate collapses common.
1–2		627			Increased dome collapses and mild explosive activity after 3 July 1998
2	27 Nov 99–28 Jul 03	1339	336	2.9	Largest dome built to date after two major collapses. Late increase in pyroclastic flows, ends in wholesale collapse of dome.
2–3		735			Two short intervals of no extrusion. Very low residual activity
3	1 Aug 05–20 Apr 07	627	282	5.3	Precursory phreatomagmatic. One wholesale collapse, ends with largest dome in place.
3–4		465			Very low residual activity
4	28 Jul 08–3 Jan 09	158	39	2.9	Two short (month) phases. Explosions and extrusion on the western flank of dome

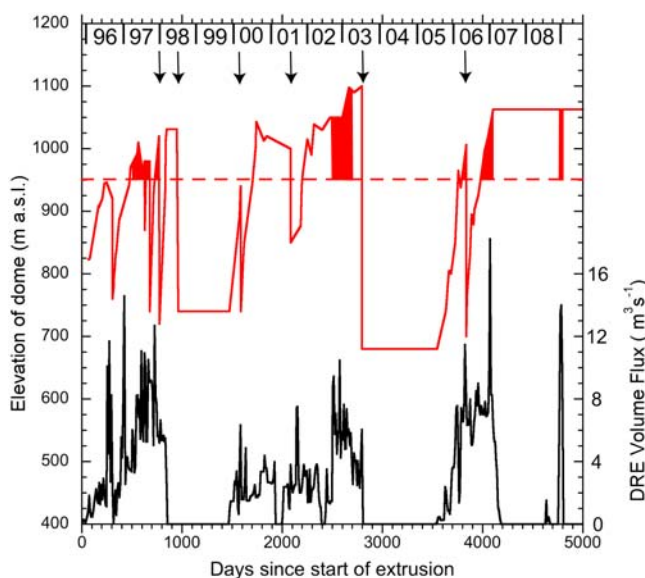


Figure 3. Variation of the DRE volume lava flux throughout the eruption derived from volume estimates at 10-day intervals with linear interpolation where necessary. The upper curve is the elevation above sea level (a.s.l.) of the summit of the lava dome and the red shaded areas satisfy the two criteria: >950 m, >5 m^3s^{-1} . The arrows mark the occurrence of the collapses with volumes >20 M m^3 discussed in the text.

modelled as the filling and emptying of a shallow, dyke-like body [Costa *et al.*, 2007].

4. Discussion

[15] Figure 3 shows the changing elevation of the dome. It is only when the dome's summit grows above about 950 m a.s.l. (dashed line in Figure 3) that collapse-derived pyroclastic flows can escape the crater in directions other than to the east [Wadge, 2009]. The hazard from the volcano increases substantially under these conditions as inhabited areas to the northwest can be threatened by large pyroclastic flows. In particular, the combination of a tall dome and high flux (>5 m^3s^{-1}) tends to initiate larger collapse events [Calder *et al.*, 2002; Watts *et al.*, 2002] and these were times of particular concern (red shaded areas in Figure 3) for risk management. Of the six largest collapse events (>20 M m^3) three (3 July 1997, 20 March 2000 and 29 July 2001) occurred outside these conditions but sent their pyroclastic flows relatively harmlessly to the evacuated east of the island.

[16] The decadal-scale production of lava at SHV has been approximately steady state, consistent with a constant influx of basaltic magma into a large crustal reservoir of andesitic magma [Devine *et al.*, 2003]. The episodic nature of lava extrusion is in contrast to the much more continuous flux of sulphur dioxide, thought to be a proxy for the rate of interaction between basalt and andesite magmas within the crustal magma reservoir [Christopher *et al.*, 2010]. The similar flux behaviour of episodes 1 and 3 suggests the repetition of a characteristic cycle of magma storage and release. The early acceleration of flux in both of these episodes may be the result of a transition of rheological

behaviour required to achieve higher conduit flux (e.g., removal of degassed lava [Sparks *et al.*, 1998]). The end period of deceleration could be a result of the fall of overpressure in the magma reservoir when replenishment is less than withdrawal. One might also expect the lava flux to fall as the elevation of the dome increases, requiring a greater proportion of the magma overpressure to overcome the increased head of magma to reach the vent. Although this effect can be inferred over some short intervals [Hale *et al.*, 2009], it is not evident generally over the whole eruption in the data used to create Figure 3, indeed the highest flux levels have occurred on domes above 950 m a.s.l..

[17] The durations and volumes of episodes 3 and 4 have been less than those of episodes 1 and 2, though the episode-averaged fluxes have been similar. Such an evolving pattern could be explained if the overpressure within the magma reservoir were to fall by a greater amount for the outflow of a unit volume of magma as the eruption progresses. However, the short-term (~10- to 15-day) periods of high lava flux (>10 m^3s^{-1}) seen in both episodes 3 and 4 (Figure 3) suggest that a separate mechanism, such as elastic-walled dyke storage acting at shallower levels [Costa *et al.*, 2007], is responsible for these.

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